

Relativistic outflows from X-ray binaries (a.k.a. ‘Microquasars’)

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Abstract. In this review I summarise the observational connections between accretion and relativistic outflows – jets – in X-ray binaries. I argue that jets are likely to be a fairly ubiquitous property of X-ray binaries as a whole, an assertion which can be tested by further observations of the Atoll-type X-ray binaries. I discuss broad patterns that are emerging from these observational studies, such as a correlation between ‘hard’ X-ray states and the presence of radio emission, and the related anti-correlation between jet strength and mass-accretion rate as inferred from X-ray studies alone. I briefly discuss possible future directions for research and compare X-ray binary jets to those from Active Galactic Nuclei and Gamma Ray Bursts.

1 History and Introduction

There has been a great deal of renewed interest in the past half a decade or so in the phenomena of relativistic outflows, or ‘jets’ from binary systems in our own galaxy. These are often referred to as ‘microquasars’ because of the apparent similarities with the Quasars, or with Active Galactic Nuclei (AGN) in general. The particular type of stellar binary systems in which these jets seem to originate are the X-ray binaries (XRBs), so-called because they are powerful sources of X-ray radiation. In XRBs a more-or-less ‘normal’ star loses matter to a compact collapsed companion, either a neutron star or a black hole; it is generally accepted that the accretion of material by the compact star, a process far more energetically efficient than nuclear fusion, is the source of the enormous power output of these systems (which can exceed in some cases 10^{38} erg s⁻¹, or the Eddington luminosity for a one solar mass object). Since the power source of AGN is similarly believed to be accretion of matter by a collapsed object, in this case a supermassive (10^6 – 10^9 M_⊙) black hole, the term ‘microquasar’ is more than simply an indicator of similar morphologies (ie. accretion, jet) but maybe also of similar physics. Therefore understanding such sources is important not only in the context of accretion physics and the evolution of ‘local’ systems, but maybe also for our broader understanding of the physics and evolution of the powerhouses of the universes, the AGN.

Fig 1 is a schematic of a generic X-ray binary, indicating the (probable) sites from which emission at different energies originates. Note that the observable spectral extent of such systems can be very broad – the classical black hole candidate (BHC) XRB, Cyg X-1, is a well-detected source from ≤ 1 GHz in the radio band to ≥ 1 MeV in γ -rays, a range of 10^{12} in photon energy. Most

schematics, certainly until a few years ago, would not have included the jet, and one of the goals of this paper will be to discuss exactly how ubiquitous is this feature in XRBs. It is interesting to note that the jet, when present, is by far the largest structure directly associated with the XRB in general, and accretion process in particular, and the only one of the structures indicated in Fig 1 which has actually been directly observed (in radio images – e.g. Fig 2).

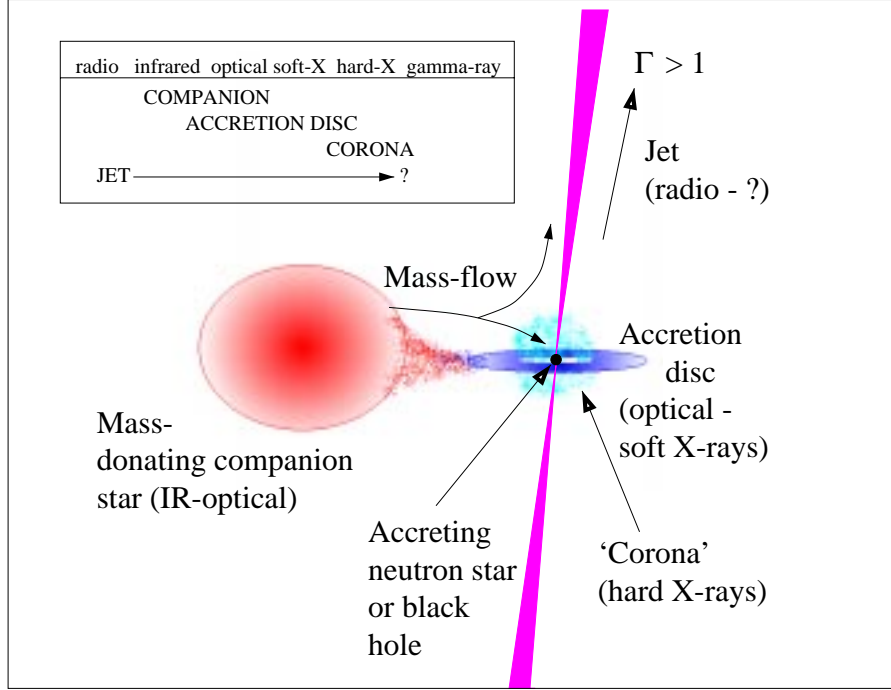


Fig. 1. A schematic of the generally accepted structure of a ‘typical’ X-ray binary system, indicating the locations of the sites believed to correspond to observed emission at different wavelengths.

Jets from XRBs as a phenomenon were first discovered from SS 433 (Spencer 1979; Hjellming & Johnston 1981a,b), a highly unusual system in many ways. The source displays optical (and infrared and X-ray) emission lines which show periodic Doppler shifts indicating a precessing bipolar outflow with velocity $v = 0.26c$; the radio jets appear to precess as predicted from the optical lines. The (apparently¹) rather well-defined and only mildly relativistic velocity (bulk Lorentz factor $\Gamma = (1 - v^2/c^2)^{-1/2} = 1.04$) are unique amongst ‘relativistic’ jet sources. Importantly, SS 433 is the only system, XRB or AGN, for which atomic emission lines have been associated with the outflow, thereby establish-

¹ scepticism is healthy

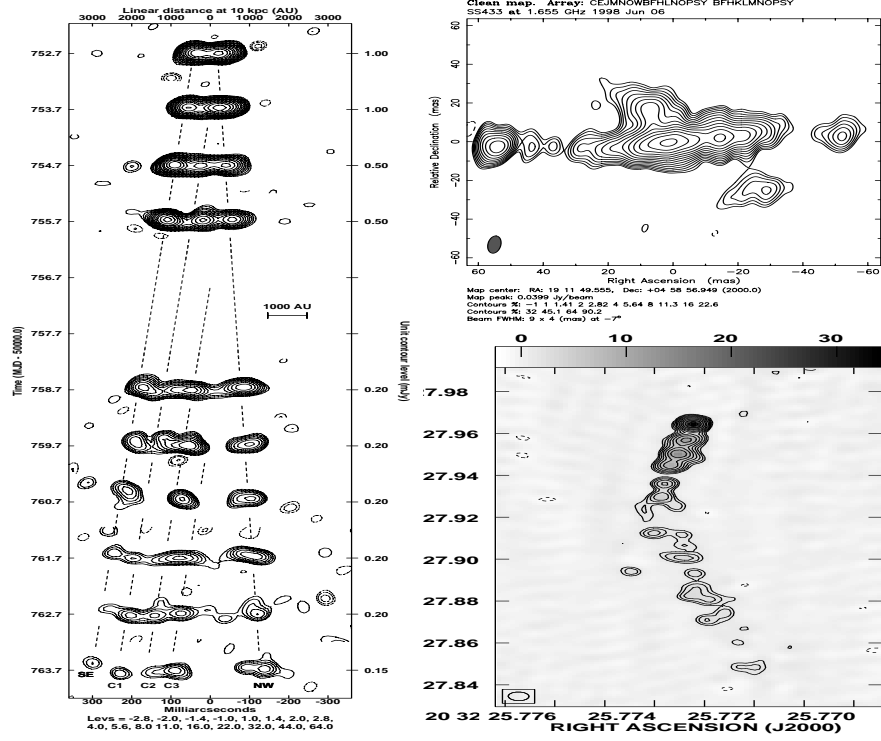


Fig. 2. Recent radio observations of three famous XRB jet sources. Left: A sequence of images of (apparent superluminal) ejections from GRS 1915+105 observed with MERLIN (Fender et al. 1999a). Top right: A recent combined EVN/VLBA image of SS 433 (Paragi et al. 2001). Lower right: a VLBA image of a one-sided curved jet from Cyg X-3 following a major radio flare (Mioduszewski et al. 2001).

ing a baryonic content (more of this later). The significant and variable linear polarisation of the jets confirmed the synchrotron interpretation for the origin of the radio emission.

Over the subsequent 15 years, a handful of other XRBs (e.g. Cyg X-3, Cir X-1, 1E 1740.7-2942, GRS 1758-258), were identified as being associated with radio jets. In the case of Cyg X-3, an apparent velocity of $\sim 0.3c$ was measured (Geldzahler et al. 1983). Perhaps all XRB jets would turn out to have a velocity of $\sim 0.3c$? This picture was comprehensively refuted in 1994 when Mirabel & Rodríguez (1994) discovered apparent superluminal motions in multiple ejections from the XRB GRS 1915+105. While distance-dependent, interpretations of the intrinsic velocity of the ejecta suggested $v \geq 0.9c$, significantly relativistic ($\Gamma \geq 2$). Clearly XRBs could eject material at extremely high velocities, comparable to those observed in AGN (where the phenomenon of apparent superluminal motion is relatively commonly observed and relatively easily explained as a geometric effect – e.g. Rees 1966; Zensus & Pearson 1987; Gomez et al. 2000). Shortly after

the observations of GRS 1915+105, a second ‘superluminal’ XRB, GRO J1655-50, was discovered (Tingay et al. 1995; Hjellming & Rupen 1995). Since GRO J1655-40 was demonstrated to be a strong BHC (Bailyn et al. 1995 and several subsequent papers), it was widely concluded that GRS 1915+105 was a BHC, something supported but never confirmed dynamically by further observations. Less certainly, it was asserted that the apparent dichotomy between the $\sim 0.3c$ sources (i.e. SS 433 and Cyg X-3) and the $\geq 0.9c$ sources (ie. GRS 1915+105 and GRO J1655-40) reflected the difference in escape speeds from the vicinity of neutron stars and black holes respectively (e.g. Livio 1999). However, at this stage it was still generally perceived that relativistic jets, as a property of X-ray binaries, were a rare phenomenon, a feature common only to a small group of ‘unusual’ systems. Recent radio images of three of the most famous jet sources are presented in Fig 2. It is worth reminding the reader that, as in the cases of AGN and GRBs, the outflows are relativistic in *two* senses – ie. they have relativistic ($1 < \Gamma < 100$) bulk velocities (ie. the proper motions we can resolve in radio images) and in addition are comprised of populations of relativistic particles ($1 < \gamma < 10000$) which, in spiralling around field lines in the magnetised plasma, produce the observed synchrotron emission.

It now seems likely that jets from XRBs are not so rare, and that for certain broad classes of X-ray binaries, maybe even the majority, the jet is as integral a part of the mass transfer process as the accretion disc. Furthermore, the apparent dichotomy in bulk velocities also no longer appears to be valid, with Fomalont, Geldzahler & Bradshaw (2001a,b) clearly establishing outflow velocities significantly higher than $0.3c$ from the neutron star binary Sco X-1 (and besides, there is no clear evidence that either SS 433 or Cyg X-3 host neutron stars and not black holes, anyway!). In this review I shall try to summarise the state of existing knowledge, and what appear to be fruitful avenues for further observational and theoretical study. The key question before we can advance to this stage is however, just how important are jets for the physical processes occurring in X-ray binaries ? I hope to answer this in the next section by establishing their near-ubiquity.

2 The near-ubiquity of jets from X-ray binaries

In the following, I shall make the assumption that any detection of radio emission corresponds to evidence for jet production (in much the same way as detection of X-rays is taken as evidence for accretion processes). This is based upon the qualitative argument that whenever we have resolved radio emission it has had a jet-like appearance (except, perhaps, in the case of the unusual transient CI Cam in which a more isotropic radio nebula seems to have formed – Mioduszewski et al., in prep), and on the following more quantitative argument – for a maximum brightness temperature of $\sim 10^{12}K$ for the synchrotron process, a flux density of ~ 5 mJy at 5 GHz (quite weak) corresponds to a physical size of $\sim 10^{12}$ cm at a distance of 5 kpc. This is an order of magnitude larger than the typical

orbital separation ($\sim 10^{11}$ cm) of a low-mass X-ray binary, and so the simplest explanation is that such a large structure is maintained by an outflow.

In terms of accretion and jet production, the most useful separation into classes of X-ray binaries is between neutron stars and black holes. I have attempted to do this both in the following sections, and also in table 1, in which approximate numbers of radio detections as a fraction of total known populations is indicated. Catalogues of XRBs with broad classifications can be found in van Paradijs (1995) and Liu, van Paradijs & van den Heuvel (2000,2001).

Class	Fraction as radio sources
BHCs (persistent)	4 / 4
BHCs (transient)	$\sim 15/35$
NS (Z)	6 / 6
NS (Atoll)	$\sim 5/100$
NS (XRP)	$\sim 0/80$

Table 1. Approximate numbers of radio detections (=jet production) in the different types of XRBs. Clearly detection of a large number of Atoll sources holds the key to unambiguously establishing (or not) the ubiquity of jets in XRBs.

Note that while the fraction stated in table 1 for the BHC transients is $\sim 15/35$, for those transients for which *any* radio observation was reported, the fraction is 15/16 (Fender & Kuulkers 2001) – how much this reflects non-publication of non-detections is unclear.

2.1 Neutron stars

The three broad classes of accreting neutron star, and the relation between X-ray and radio properties, are summarised in Fig 3.

The Z sources These are the brightest persistent X-ray sources in the sky (the single brightest nonsolar X-ray source, Sco X-1, is the prototype of the group; Hasinger & van der Klis 1989). There are six in our galaxy, and possibly one in the LMC. The Z sources are thought to contain neutron stars with relatively low ($\leq 10^9$ G) dipole magnetic fields, accreting at or near the Eddington limit. All six galactic systems are variable but reliable radio sources, with a comparable radio luminosity (when on the ‘horizontal branch’ – Penninx 1989; Fender & Hendry 2000). The ‘Z’ refers to the pattern traced out in the X-ray colour-colour diagram (CD) in which three (possibly four) branches smoothly connect. Penninx et al. (1988) found that the radio emission was strongest on the ‘Horizontal Branch’ and weakest on the ‘Flaring Branch’ in the Z source GX 17+2, an apparent anti-correlation with accretion rate, \dot{m} as deduced from X-ray observations alone. This relation between X-ray ‘state’ (as described by the branches of the Z) and radio emission seems to be a property common to all the Z sources (Hjellming

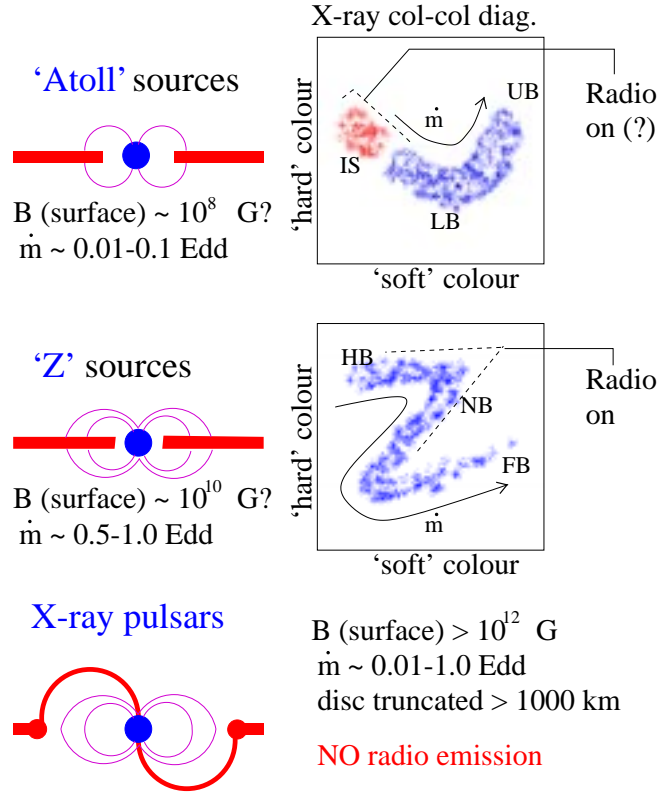


Fig. 3. A rough schematic of the three types of neutron star X-ray binary, a rough physical interpretation, and indication as to which states are associated with the presence of radio emission. For the Atoll sources, this association is currently speculative. Abbreviations are IS=Island State, LB=Lower Banana, UB=Upper Banana, HB=Horizontal Branch, NB=Normal Branch, FB=Flaring Branch.

& Han 1995 and references therein). Recently high-resolution radio observations have revealed unequivocal evidence for a variable jet-like structure associated with Sco X-1 (Bradshaw, Fomalont & Geldzahler 1999; Fomalont, Geldzahler & Bradshaw 2001a,b). The observations, of a variable core and moving, variable lobes, are interpreted as the impact of a highly relativistic beam on the ISM, producing the advance of radio 'hotspots' (Fomalont et al. 2001a,b). Given the similarities in their radio properties, and the resolved jet in Sco X-1, the simplest conclusion (ie. using Occam's razor) is that all Z sources produce relativistic jets. Furthermore, the 'unusual' system Cir X-1 has some Z-like properties (Shirey, Bradt & Levine 1999) and is a source of radio jets from arcsecond to arcmin angular scales (Stewart et al. 1993; Fender et al. 1998).

The Atoll sources In the original classification of Hasinger & van der Klis (1989) and subsequent works, the Atoll sources were discussed as a separate small subgroup of bright low mass X-ray binaries with relatively low magnetic fields, accreting at lower rates than the Z sources (e.g. van der Klis 1995 for more details). Since then it seems likely that Atoll-like properties may be shared by the majority of low-field accreting neutron stars (van Paradijs, Ford, van der Klis, private communication) and so we shall adopt this viewpoint here. If this is the case then the Atoll sources, which will now include the groups of ‘bursters’, ‘dippers’ etc., are the largest class of catalogued X-ray binaries (see table 1). Little is known about the radio properties of the Atoll sources, except that, as a population, they are faint sources (typically < 1 mJy at cm wavelengths – Fender & Hendry 2000). The only Atoll source to be regularly and repeatedly detected at radio wavelengths was, until recently, the bright system GX 13+1 (Garcia et al. 1988). More recently other Atoll systems have been discovered to have radio counterparts (e.g. 4U 1728-34/GX 354+0 – Martí et al. 1998), and sources with known transient radio counterparts have been discovered to be Atoll-like in nature (e.g. Aql X-1 – Reig et al. 2000). So while it is clear that as a population Atoll sources are not particularly radio-bright, it is also clear that they do produce detectable radio emission under certain conditions. This then implies that the majority of catalogued low-mass X-ray binaries are capable of producing a radio jet. However, until a jet is directly resolved from an Atoll source (a key future observation) this will remain unproven.

The X-ray pulsars These systems possess much stronger magnetic fields ($\geq 10^{11}$ G) than the Z or Atoll sources, which results in the disruption of the accretion flow at a distance of several thousand km from the neutron star surface (e.g. Bildsten et al. 1997 and references therein). As a population they are significantly fainter than even the Atoll sources, and no strong-field X-ray pulsar has ever been detected as a radio synchrotron source (Fender & Hendry 2000). Thus the strong possibility exists that such systems do not produce jet-like outflows, due to the extreme disruption of the accretion flow. Deep radio observations of some nearby X-ray pulsars would be useful to further constrain this.

NS transients Neutron star soft X-ray transients (Chen, Shrader & Livio 1997; Campana et al. 1998) can probably be classified as Atoll-like (e.g. the case of Aql X-1 – Reig et al. 2000). As with the BHC transients, there seems to be a discrete ejection of synchrotron emitting material associated with the sudden increase in luminosity at the start of the outburst. This manifests itself in a transient radio event which becomes optically thin within a few days (presumably due to decreasing self-absorption as the ejected component expands) and then fades away monotonically (Hjellming & Han 1995; Fender & Kuulkers 2001).

Several transients contain high field accreting X-ray pulsars (e.g. Bildsten et al. 1997) and, as with the more persistent sources of this type, none have ever been detected as radio synchrotron sources (Fender & Hendry 2000).

2.2 Black hole candidates

The description of the accretion state of the BHCs differs from that of the neutron stars as it is perceived that probably all black holes can, under the right conditions, achieve all states – ie. it is not currently perceived that there are different ‘types’ of black hole (the only obvious distinguishing characteristic would be the black hole spin). These ‘states’ are summarised in Fig 4. Note that while it was originally supposed that the states were a more or less one-dimensional function of mass accretion rate, which could itself be tracked via soft X-ray (disc) flux (see e.g. the pattern of behaviour in GRO J1655-40 – Mendez, Belloni & van der Klis 1998), it now seems clear that the picture is not so simple. One problem is that the same ‘state’ in terms of the X-ray spectral and timing properties can be reproduced at extremely different flux levels (e.g. Homan et al. 2001).

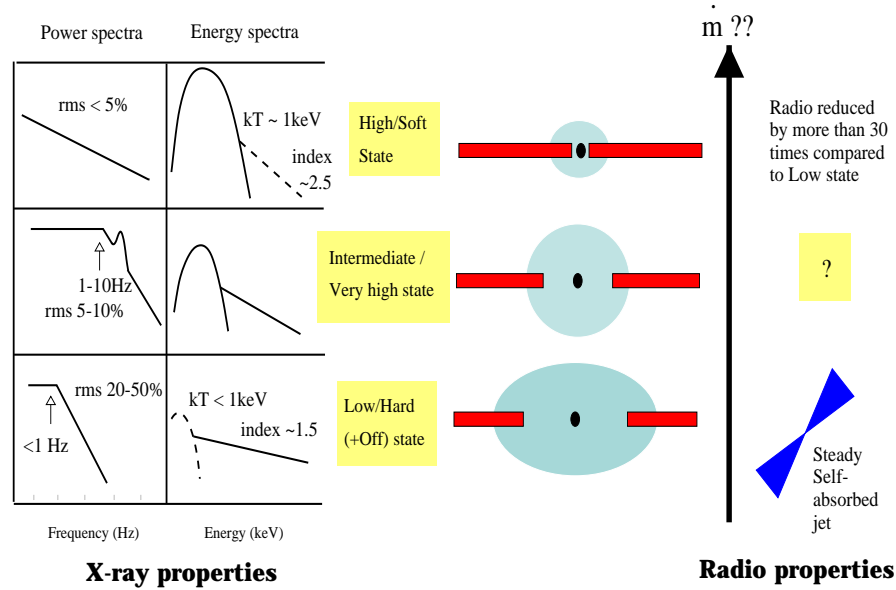


Fig. 4. BHC spectral states, as classified by their X-ray spectral and timing properties. A rough physical interpretation, based on the X-ray data alone, is indicated, as is the relation to radio emission. BHC transients typically, although not exclusively, transit from undetectable levels to the soft state in a short period of time. The relation of states to mass accretion rate, previously thought to be quite clear, is now less certain.

The two most distinct states are the the Low/Hard and High/Soft states, being the extremes of ‘nonthermal’ and ‘thermal’ spectra respectively (this is an oversimplification). There also exists a hybrid state, labelled the Very High or Intermediate state, which is less commonly observed than either the Low/Hard or High/Soft states, whose relation to radio emission, and hence presumably jet production, is unclear (but see Corbel et al. 2001).

The Low/Hard state The Low/Hard X-ray state (historically called ‘Low’ because it is generally weaker than the High/Soft state in the soft X-ray band, and ‘Hard’ since it is dominated by a nonthermal power-law component which peaks at hard X-ray (≥ 50 keV) energies) is the state in which the four persistent BHCs in our galaxy spend most of their time (I consider these four to be Cyg X-1, GX 339-4, 1E1740.7-2942 and GRS 1758-258, although it should be noted that, at the time of writing, GX 339-4 has been at extremely low levels for over a year and consistently displays a larger amplitude of X-ray variability than the other systems).

In the early 1970s a transition from the High/Soft (possibly only ‘Intermediate’ – see discussion in Belloni et al. 1996) to Low/Hard X-ray states in Cyg X-1 was observed to be coincident with the appearance of a radio counterpart to this source (Tananbaum et al. 1972). It has since been established that while the source is in the Low/Hard state, which seems to be most of the time, it steadily emits a relatively low level (typically 5-15 mJy at cm wavelengths) of radio emission (e.g. Brocksopp et al. 1999). The spectrum of the radio emission is remarkably flat and extends to at least the millimetre regime (Fender et al. 2000b). Furthermore, the radio emission is modulated at the 5.6-day orbital period of the system (Pooley, Fender & Brocksopp 1999). All of this evidence taken together suggests that the flat spectrum radio emission arises in a continuously-generated, partially self-absorbed compact jet from the system (with the orbital modulation possibly due to variable free-free absorption in the dense stellar wind of the OB-type mass-donor – Brocksopp 2000). Confirmation of this hypothesis appears to have recently been achieved with VLBA images of the system clearly resolving an asymmetric jet from a compact core (Stirling, Garrett & Spencer 1998; Stirling et al. 2001).

The other three persistent Low/Hard state systems also show flat radio spectra, and the two Galactic centre sources, 1E1740.7-2942 and GRS 1758-258, are associated with parsec-scale jet/lobe structures (the original motivation for the name ‘microquasar’; Mirabel et al. 1992; Rodríguez, Mirabel & Martí 1992; Mirabel 1994). Furthermore, in both Cyg X-1 and GX 339-4 there is an approximately linear relation between the X-ray flux (dominated by the non-thermal power-law) and the radio emission (Brocksopp et al. 1999; Corbel et al. 2000) indicating a clear coupling between accretion (presumed to be reflected in the strength and spectrum of the X-ray emission) and outflow. While GX 339-4 is the one source for which the jet has probably not been reliably resolved, it is the one for which linear polarisation (at the level of a few %), has been measured (Corbel et al. 2000), supporting the synchrotron-emitting jet model.

While most BHC transients are observed to evolve rapidly (hours) from a ‘quiescent’ state to the High/Soft state (and are generally accompanied by an optically thin radio outburst – e.g. Fender & Kuulkers 2001), a few X-ray transients have been observed to spend an extended period in the Low/Hard state. A careful comparison of these Low/Hard state transients reveals that, following an initial optically thin radio event, they develop low-level, inverted-spectrum radio components. These were originally dubbed ‘second stage’ radio sources (e.g. Hjellming & Han 1995 and references therein). In Fender (2001) it is argued that these components are the same as the flat/inverted spectrum components observed from the persistent sources in the Low/Hard state, and furthermore that such spectral components, and therefore compact jets, are a general property of the Low/Hard state.

The High/Soft state Early observations of Cyg X-1 (e.g. Tananbaum et al. 1972) suggested that the radio emission from the source was suppressed when in the High/Soft state (compared to the Low/Hard state). Despite the great accessibility of this system to the world’s radio telescopes, a chance to test this hypothesis during a transition of the source to a soft X-ray state in 1996 was missed. However, observations near the end of the soft state support a scenario in which radio emission is stronger during the Low/Hard state (Zhang et al. 1997).

It was a year-long transition to the High/Soft state by GX 339-4 in 1998 in which the ‘quenching’ of the radio emission compared to the Low/Hard state was definitively established (Fender et al. 1999; Corbel et al. 2000). Radio monitoring of the source revealed the cm wavelength radio emission to have dropped by a factor of ≥ 25 during the High/Soft state, and to return to its previous levels once the source resumed the Low/Hard state (Fig 5).

The Very High/Intermediate state Little is clearly understood about the radio emission during the (comparatively rare) Very High/Intermediate state of BHCs, in which both thermal (disc) and nonthermal (power-law) spectral components can be present. Is it the presence of the nonthermal component, or the absence of the thermal component, which is necessary for the production of radio emission? Recent observations (Corbel et al. 2001) suggest the latter, but further observations of this state are required.

BHC transients BHC X-ray transients (e.g. Chen et al. 1997; Charles 1998) are generally associated with radio outbursts (e.g. Hjellming & Han 1995; Fender & Kuulkers 2001), which have been resolved on a small number of occasions into discrete ejections, sometimes multiple, of radio emitting components (e.g. GRO J1655-40 – Tingay et al. 1995; Hjellming & Rupen 1995).

In most cases the transients seem to transit from ‘quiescence’ (which may be some very low-level version of the Low/Hard state described above) to the High/Soft state in the space of a few days or less. However, in some rare cases

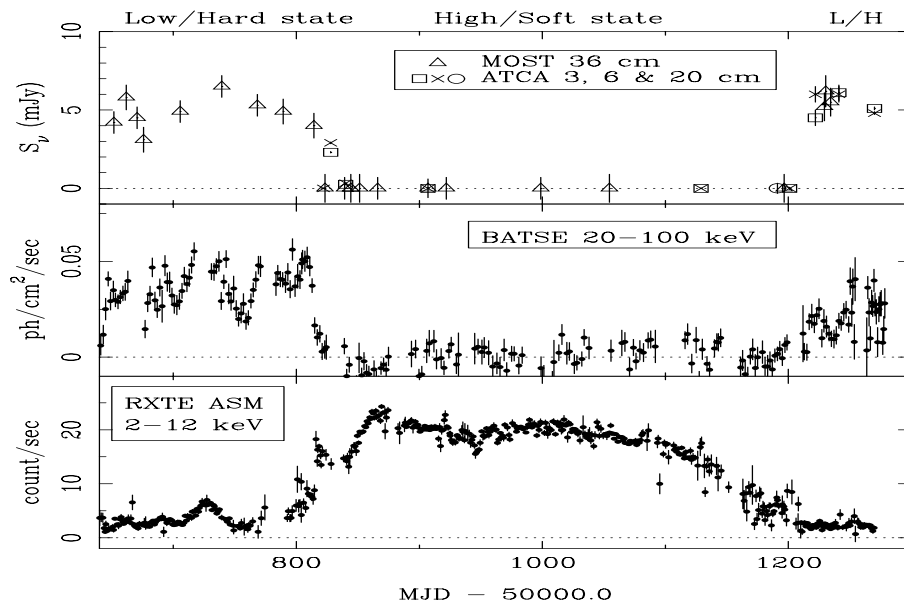


Fig. 5. Simultaneous ‘quenching’ of the radio (top panel) and hard X-ray emission during a year-long high/soft state in the black hole candidate GX 339-4 (from Fender et al. 1999; see also Corbel et al. 2000).

(e.g. Fender 2001; Brocksopp et al. 2001) a transient will ‘only’ make it to the Low/Hard state. Whichever ‘branch’ the transient takes, it seems that the initial rise is generally associated with a discrete ejection event (Fender & Kuulkers 2001), sometimes multiple events (e.g. Kuulkers et al. 1999). Subsequently, if the source ‘achieves’ the High/Soft state, there appears to be no re-emergence of core radio emission (and so we can assume the radio jet is ‘switched off’ and any radio emission we observe is physically decoupled from the ongoing accretion process); if it instead finds itself in the Low/Hard X-ray state a flat or inverted-spectrum component emerges (Fender 2001).

GRS 1915+105 While one of the aims of this review is to establish that jets are not a bizarre property of some small subset of XRBs, but rather a more ubiquitous feature, one source, GRS 1915+105, still deserves a mention on its own. The source displays a remarkable and unique range of X-ray behaviour which can however be broken down into transitions between three broadly-defined ‘states’ (Belloni et al. 2000). It was also the first system for which we had direct evidence of highly relativistic flows (Mirabel & Rodríguez 1994) and displays an extraordinary variety of radio behaviour (e.g. Pooley & Fender 1997), most of which can (presumably) be associated with the formation of synchrotron-emitting jets.

One of the three ‘states’ into which any X-ray light curve of GRS 1915+105 can be deconstructed (state ‘C’) is broadly analogous to the Low/Hard state

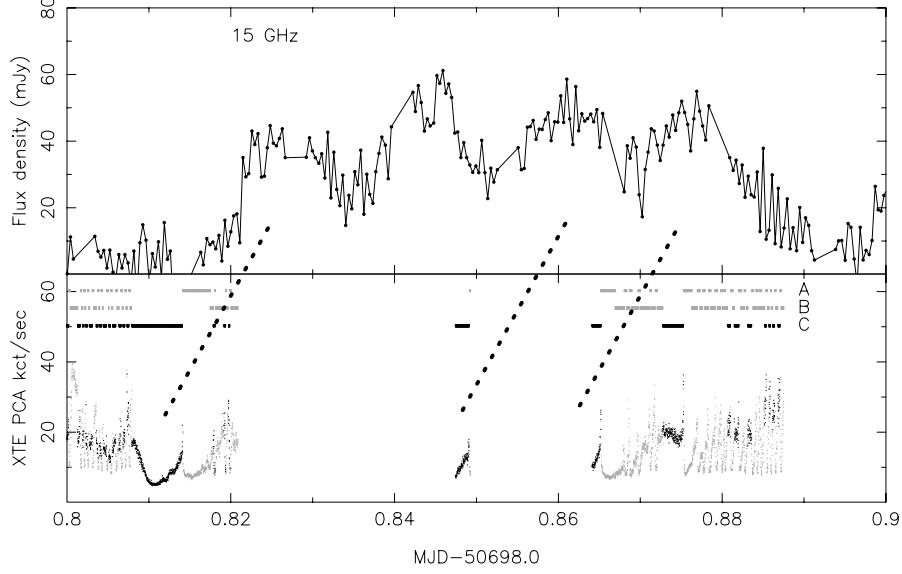


Fig. 6. The one-to-one correspondence, in GRS 1915+105, of brief (minutes) transitions into state ‘C’, roughly analogous to the Low/Hard state in more traditional BHCs, with the formation of discrete radio oscillation events. Four radio events are observed to be associated with a dips into the hard state – gaps in the X-ray light curve are due to Earth occultations, and there was almost certainly a hard dip associated with the second radio event as well. The delay is probably due to the time required for self-absorption of the radio emission to decrease (as the ejecta expand). From Klein-Wolt et al. (2001).

of traditional BHCs, being dominated by a power-law component in the X-ray band. From a comparison of many hours of overlapping X-ray and radio observations, we are confident that radio oscillation events are directly, and only, associated with these hard states in this source (Fig 6; Klein-Wolt et al. 2001), although there are alternative opinions expressed in the literature (e.g. Naik & Rao 2000).

GRS 1915+105 shows other extraordinary properties, as if attempting to provide all the observational data we need to understand the ‘disc-jet’ coupling on its own. For example it was the first source for which there was unequivocal evidence for infrared synchrotron emission (Fender et al. 1997; Eikenberry et al. 1998, 2000; Mirabel et al. 1998; Fender & Pooley 1998; 2000) and is the clearest example of a flat-spectrum core being resolved into a quasi-continuous jet (Dhawan, Mirabel & Rodríguez 2000; Feretti et al. 2001).

3 Connections

Some broad patterns are now beginning to emerge from these studies; these patterns are clues to generic properties of jets, their coupling to the accretion process and so on. In no particular order, these include:

- A broad correlation between hard X-ray states and radio emission, in particular in BHCs. Meier (2001) takes such observations as direct evidence for the MHD formation of jets in geometrically thick accretion flows. These hard X-ray states are generally interpreted as arising via inverse Comptonisation (Poutanen 1998 and references therein) in a ‘corona’ and/or an advection-dominated accretion flow (ADAF; e.g. Esin, McClintock & Narayan 1997). It is interesting to note that, to my knowledge, in every case where an ADAF has been invoked to explain the optical–X-ray spectrum in XRBs, radio emission is present (and yet is not fit by ADAF models).
- A related point is that in all types of X-ray binary for which we have a clear picture, the strength of the jet appears to be *anticorrelated* with the mass accretion rate as inferred from X-ray spectral and timing studies alone (e.g. Figs 2,3; Belloni, Migliari & Fender 2000). Jets may well turn out to be an important factor in the state transitions associated with BHCs, Z sources and probably also Atolls.
- The jet, however it is formed, whether via MHD or some other ‘black box’ really seems to carry a lot of the accretion power – in the case of the hard state of BHCs it seems inescapable that the jet requires at least 10% of the accretion energy budget – since current models often attempt to fit observations to a rather higher degree of accuracy than this its effect can presumably not be ignored.

4 Forwards

In Fig 7 I attempt to briefly summarise the state of play of research into X-ray binary jets. A key point is the ubiquity of jets; it is hoped that I have by now convinced the reader that it is at least *possible* if not *likely* that jets are important for the majority of X-ray binary systems. Taking this as established, I have outlined the areas in which important research can be done via either

- An empirical, ‘energetics’ approach, in which the exact way in which the jet extracts energy and angular momentum from the accretion flow is not key, but rather estimating *how much* of these quantities are associated with the jet, is.
- A ‘physics’ approach, in which we really try to probe the physics of what is happening – ie. how are the particles accelerated, how are the inflow and outflow physically coupled, what knowledge can we extract about solid surfaces/event horizons associated with the compact object, etc.

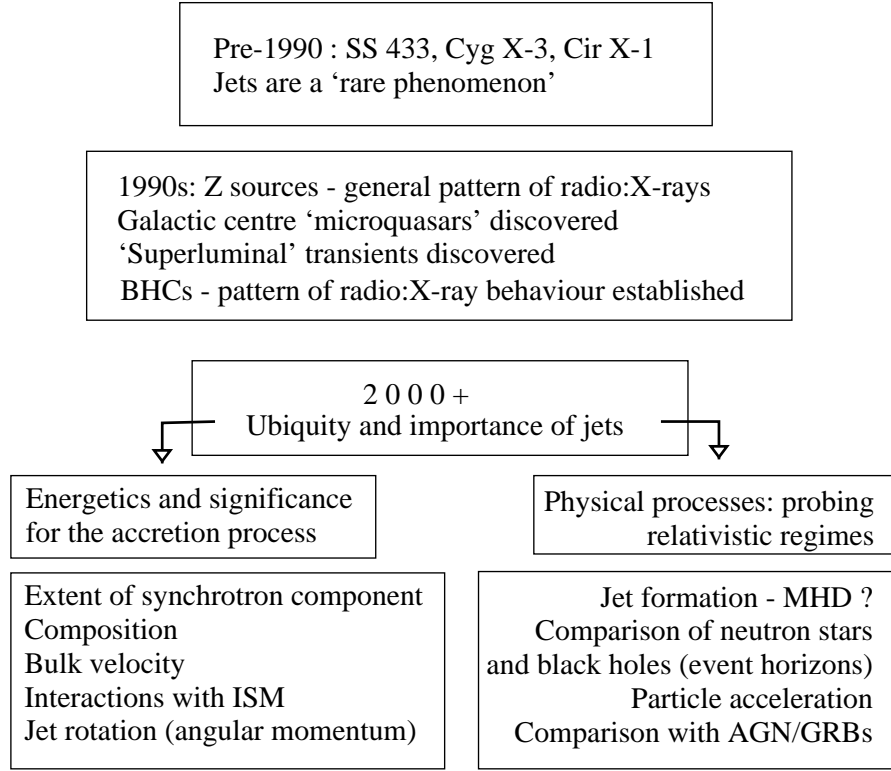


Fig. 7. A schematic indication of where we are now with research into jets from X-ray binaries, and some possible future directions. Central to this scheme is an understanding of how ubiquitous is the jet phenomena for X-ray binaries.

It is fair, I think, to say that while the second approach must be the ultimate aim, it is only via the broader approach in which the significance (without the details) can be established, that the research interest in the detailed physics can be established.

4.1 Energetic and dynamical significance of jets

Spectral extent and power of synchrotron component It was already noted that transient ejection events could require a very large rate of power injection, and may be energetically significant during the outburst phase of transients (e.g. Mirabel & Rodríguez 1994). While Kaiser, Sunyaev & Spruit (2000) argued that the required energy input could be spread over a longer timescale,

at least in one case, the repeated oscillation/ejection events in GRS 1915+105, this cannot be occurring (Fender & Pooley 2000).

In the persistent sources, notably the black holes in Low/Hard states, there are strong arguments that the self-absorbed synchrotron spectrum extends to at least the near-IR or optical bands (Fender 2001; Brocksopp et al. 2001; Fender et al. 2001). Since the jets are likely to be radiatively inefficient (as are AGN jets, see e.g. Celotti this volume), then the total jet power may begin to approach or even exceed the broadband X-ray luminosity, traditionally taken to be the best measure of accretion rate. In the case of the Low/Hard state transient XTE J1118+480 (which has been dynamically established to contain a black hole – McClintock et al. 2001), the ratio of total jet power to X-ray luminosity, if the synchrotron spectrum extends *only* to the near-infrared, is of order $P_J/L_X \sim 0.01\eta^{-1}$ where η is the radiative efficiency of the jet (Fender et al. 2001). For both X-ray binaries and AGN, it is likely that $\eta < 0.1$, giving $P_J \geq 0.1L_X$ – so even in a very conservative estimate, the jet power is at least 10% of the total accretion luminosity and cannot seriously be ignored.

Even more intriguingly, if the self-absorbed synchrotron component extends to the optical band or beyond, then comparison of the broadband radio–optical–X-ray spectra of BHCs in hard states show that the optically thin component should have a significant role to play in the X-ray band. In fact, Markoff, Falcke & Fender (2001) show that for XTE J1118 the jet can even fit almost the entire broadband spectrum, dominating ($> 90\%$) the power output of the system in the low/hard X-ray state (Fig 8). For the neutron stars the data are sparser, but Fomalont et al. (2001a,b) argue that the jet power in Sco X-1 is at least an order of magnitude greater than the observed X-ray luminosity. Furthermore, sources such as SS 433 and LS 5039 (Paredes et al. 2000) are very weak in the X-ray band by the standards of XRBs in general, yet are powerful producers of jets and maybe even γ -rays. Perhaps we should adjust our thinking to consider that X-rays are not the only tracers of accretion power at large in the universe.

Composition The question of whether or not XRB jets are in general comprised of a normal baryonic (electrons + protons) plasma or of pairs (electrons + positrons) is important both for our concept of the flow of mass in accretion, and in estimating the energetics of the outflow. For example, in the case of the repeated oscillations in GRS 1915+105 the required power in the event that each oscillation is associated with the relativistic bulk motion of a large number of protons is much greater than if the plasma is simply electron:positron pairs (Fender & Pooley 2000).

Unfortunately, with the exception of SS 433 for which atomic emission lines have been directly observed (e.g. Margon 1984), we only observe synchrotron emission from electrons (and/or positrons) in the jets and it is not straightforward to detect the presence of protons. One ray of hope is that the use of circular polarisation measurements may shed light on the composition of jets in both AGN and XRBs (e.g. Wardle 2001), although interpretations of data are not straightforward. One XRB source, SS 433, has been detected in circular

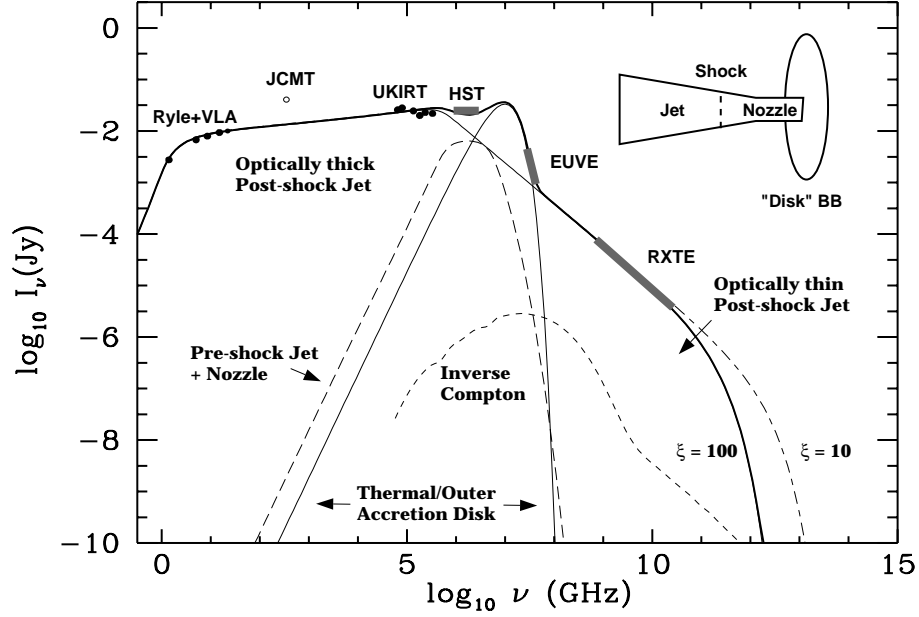


Fig. 8. Broadband radio – X-ray spectrum of the BHC XTE J1118+480 in the low/hard X-ray state, fitted by a combination of a truncated accretion disc and a jet. From Markoff et al. (2001).

polarisation (Fender et al. 2000a), but again the relation of this source to other more ‘normal’ XRBs is unclear, and more measurements are needed.

Bulk velocity Essential to our understanding of the energetics of the outflow ($E_{\text{kinetic}} \sim (\Gamma - 1) \times E_{\text{internal}}$), and also for theoretical models of jet formation and their propagation through the ISM, is the ‘terminal’ Lorentz factor of the outflows in X-ray binaries. Only SS 433 has a well-defined and only moderately relativistic flow velocity. For other systems, even the well studied ones such as GRS 1915+105, the ‘true’ bulk Lorentz factor is such a sensitive function of the assumed distance (Fender et al. 1999a) and our interpretation of the data (Bodo & Ghisellini 1995) that we cannot really be certain at all of its value.

One interesting consideration is that the similarity of the correlation between X-ray and radio fluxes in the Low/Hard state sources Cyg X-1, GX 339-4 and others (Brocksopp et al. 1999; Corbel et al. 2000; Fender 2001) may naively imply that one component cannot be strongly beamed compared to the other, or the relation would be very different from source to source, depending on inclination even if they all had exactly the same velocity. Therefore it seems likely that the bulk Lorentz factor is not exceptionally high, probably < 10 ,

although a quantitative investigation is required to tell if the available small-number statistics really are that constraining.

Jet rotation – angular momentum transport While there is much progress in understanding the energetic significance of jets from X-ray binaries, their influence (if any) on the extraction of angular momentum from the accretion flow (a necessary but poorly-understood process) remains unclear. Observations of rotating jets from X-ray binaries, especially if the amount of angular momentum could be quantitatively estimated, would be of great significance.

Interactions with the ISM Observations of interactions between XRB jets and the ISM are much less common than observations of interactions between AGN jets and the IGM; as a result we are left with one less diagnostic of the energetics of the outflow – in essence, the endpoint of the bulk of XRB jet power (in the form of kinetic energy) is unknown. In a few cases, interactions with the ISM have been observed – the BHCs 1E 1740.7-2942 and GRS 1758-258 in the galactic centre show AGN-like radio lobes (e.g. Mirabel 1994); SS 433 is clearly interacting with the surrounding radio nebula W50 (e.g. Dubner et al. 1998); Cir X-1 is surrounded by a radio nebula which seems to be powered by its radio jets (Stewart et al. 1993; Fender et al. 1998), and there are a few more examples.

Besides being additional clues as to the total power of jets, other intriguing possibilities exist which could be investigated by means of the jet-ISM interaction. For example, are XRB jets a source of cosmic rays ? do they induce star formation ?

5 Physical processes

5.1 Jet formation

Detailed numerical modelling of relativistic jets currently favour magnetohydrodynamic (MHD) models (e.g. Meier, Koide & Uchida 2001 and references therein). Can we test these models with observations of X-ray binaries ? perhaps in some ways we can – for example Meier (2001) takes the empirically derived association between hard X-ray states and radio emission in XRBs as some of the strongest observational evidence for MHD jet formation in geometrically thick accretion flows threaded by poloidal field lines.

5.2 Comparison of neutron stars and black holes

Are there any observed differences between the accretion:outflow coupling in BHCs and NS systems ? There may be some hints – firstly, in Fender & Hendry (2000) it was established that the persistent BHCs in the Low/Hard state had approximately the same radio luminosity as the Z sources on the HB. Since the Z sources are significantly more luminous X-ray sources than the Low/Hard

state BHCs, this already implied that there was some difference. In Fender & Kuulkers (2001) the ratio of peak radio to X-ray flux was compared for all reported (quasi-)simultaneous observations of X-ray transients. This ratio, or ‘radio loudness’ was found to be significantly higher for the BHCs. There are two obvious possible causes of this effect – either BHCs are more efficient at producing jets (extraction of energy from their deeper gravitational potentials?), or maybe the BHCs are underluminous at X-ray wavelengths, even in outburst, due to radiatively inefficient flows and their lack of a solid surface. The former explanation implies that we are probing to within the last few gravitational radii around the compact object; the latter may be considered evidence for black hole event horizons.

5.3 Particle acceleration and a comparison to AGN and GRBs

Part of the theme of this volume is a comparison between the physics of relativistic outflows from X-ray binaries, AGN and GRBs. I shall briefly address both of these areas here.

Particle acceleration Observation of the spectral index of optically thin synchrotron sources allows a direct probe of the underlying electron population. The synchrotron emission is produced by a (probably) nonthermal (power-law) distribution of relativistic (Lorentz factors possibly to ≥ 1000) electrons spiralling in a magnetic field. Typically this results in an observed power-law emission component at frequencies for which self-absorption is not important (ie. ‘optically thin’), for which we can define the spectral index $\alpha = \Delta \log S_\nu / \Delta \log \nu$, i.e. the observed flux density $S_\nu \propto \nu^\alpha$ (warning : many works, especially older papers on AGN, use the reverse definition, ie. $S_\nu \propto \nu^{-\alpha}$). If the power-law distribution of electrons is described as $N(E)dE = N_0 E^{-p} dE$ (where $N(E)dE$ is the number of electrons with energy in the range E to $E + dE$, and N_0 is a constant), then the observed spectral index $\alpha = (1 - p)/2$ (for a plasma in which adiabatic expansion losses dominate). Thus measurement of the optically thin spectral index directly provides information on the distribution of relativistic electrons; typically $-1 \leq \alpha_{\text{opt.thin}} \leq -0.5$, implying $2 \leq p \leq 3$.

These values are broadly consistent with those predicted for acceleration of the particles at a shock (e.g. Blandford & Eichler 1987) and are comparable to those observed in AGN. For now it seems reasonable to accept shock-accelerated power-law distributions of electrons as the origin of the observed synchrotron emission.

XRBs as mini-AGN: ‘Microquasars’ The term ‘microquasar’ is evocative and has been powerful in attracting public and scientific interest to the field of jets from X-ray binaries. It cannot be denied that there is some accuracy in it as a scientific expression, since in both AGN and X-ray binaries it seems that an accretion flow around a black hole (or neutron star in the case of the XRBs) results in the production of a powerful collimated outflow. There are

obvious differences too, such as the supply of matter for accretion (or ‘Fuel Tank’) which is clearly different in the two cases, but perhaps, since the exotic physics takes place relatively close to the black hole, where the material has presumably ‘forgotten’ where it came from, this is not important. For example, Falcke & Biermann (1996) discuss the applicability of scaling down AGN jet models to X-ray binaries. It has often been noted that since accretion timescales might be expected to scale with mass of the accretor then processes which could never be observed from an AGN in a single human lifetime may be observed many times over by the same individual from a microquasar (e.g. Sams, Eckart & Sunyaev 1996; Mirabel & Rodríguez 1999).

Has the study of XRBs shed any light yet on the physics of AGN ? this is less clear, but the prospects are good. Certainly application of many principles developed for AGN has been extremely useful in helping us to understand XRB jets without having to reinvent the wheel, and it would be nice to reciprocate. An example may be the clear relation between modes of accretion, or ‘states’, and the presence of radio jets in the BHC XRBs – is this related to the radio-loud:radio-quiet dichotomy in AGN ?

XRBs and GRBs GRBs and their afterglows are now widely believed to be associated with highly relativistic outflows (e.g. Sari, Piran & Halpern 1999; see also papers by Sari and Galama in these proceedings). Since they appear to be small-scale objects (compared to AGN) it is therefore natural to look for any connections with the jets of XRBs. Pugliese, Falcke & Biermann (1999) specifically discuss the possibility of a GRB from SS 433, and Portegies Zwart, Lee & Lee (1999) discuss the possibility of GRBs arising from a precessing jet in a ‘gamma-ray binary’. For now the jury is out on the relevance of such comparisons and models. In at least one respect, the bulk Lorentz factor (invoked to be 100 or even more in GRBs) there seems to be a significant distinction between the physics of the outflow in the two types of object.

6 Conclusions

To conclude, the study of jets from X-ray binaries is providing much exciting data on the physics of the coupling of accretion and outflow around both neutron stars and black holes. The latter in particular provide hope that we may be able to learn about the physics of black hole accretion in AGN, the powerhouses of the Universe, by studying XRBs. It is this author’s feeling that jets will turn out to be a fairly ubiquitous characteristic of the accretion process in XRBs. In order to establish this, more observations of radio emission from the NS Atoll sources, the single largest class of XRB, are required.

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